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How Cities Reshape the Evolutionary Path of Urban Wildlife

By
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The northwest corner of Newark Bay is the kind of place comedians have in mind when they mock New Jersey as a cesspool. The grim industrial coast the bay shares with the Passaic River is lined with the hulks of old chemical plants that treated their surroundings like a toilet. The most infamous of these facilities produced nearly a million gallons of Agent Orange, the toxic defoliant whose extensive use during the Vietnam War has caused generations of suffering. The Agent Orange plant discharged unholy amounts of carcinogenic dioxin—so much, in fact, that New Jersey's governor declared a state of emergency in June 1983. Though the Environmental Protection Agency has announced a $1.4 billion cleanup effort, the waters closest to Newark's Ironbound neighborhood remain highly contaminated; there are few worse spots in America to go for a swim.

And yet upper Newark Bay is not devoid of life. Beneath its dull green surface teems a population of Atlantic killifish, a silvery topminnow that's common along the Eastern Seaboard. These fish are virtually indistinguishable from most other members of their species, save for their peculiar ability to thrive in conditions that are lethal to their kin. When killifish plucked from less polluted environments are exposed to dioxin levels like those in the bay, they either fail to reproduce or their offspring die before hatching; their cousins from Newark, by contrast, swim and breed happily in the noxious soup.

Eight years ago, while he was an associate professor at Louisiana State University, an environmental toxicologist named Andrew Whitehead decided to find out what makes Newark's killifish so tough. He and his research group collected sample fish from an inlet near the city's airport and began to deconstruct their genomes, sifting through millions of lines of genetic code in search of tiny quirks that might explain the creatures' immunity to the ravages of dioxin.

In late 2014, two years after having moved to UC Davis, Whitehead zeroed in on the genes linked to the aryl hydrocarbon receptor, a protein that regulates an array of cellular functions. When most adult killifish encounter dioxin, this receptor's signaling pathway revs to life in the hope of metabolizing the chemical invader. But try as it might, the protein can't break down the insidious substance. Instead of acting as a defense mechanism, the frustrated signaling

pathway wreaks havoc during development—causing severe birth defects or death in embryos. “If you inappropriately activate this pathway when your organs are being developed, you're really hosed,” Whitehead says. But that ugly fate never befalls the Newark Bay killifish because their bodies are wise to dioxin's cunning; the genes that control their aryl hydrocarbon receptors, which have slightly different DNA sequences than those found in other killifish, lie dormant when confronted by the toxin.

As he explained in a landmark *Science* paper in 2016, Whitehead and his colleagues also discovered that Newark Bay's killifish are not alone in using this clever genetic tactic to survive in tainted water. He identified similarly resilient killifish in three other East Coast cities whose estuaries have been befouled by industry: New Bedford, Massachusetts; Bridgeport, Connecticut; and Portsmouth, Virginia. Since killifish never roam far from where they're born, these resistant populations must have developed the identical tweaks to their genomes without mixing with one another—or, put more plainly, the far-flung fish all evolved in remarkably similar ways in response to the same environmental pressures. This is compelling evidence in favor of the notion that evolution, that most sublime of nature's engines, is not some chaotic phenomenon but, rather, an orderly one whose outcomes we might be able to predict.

Whitehead's work on killifish is one of the signature triumphs of urban evolution, an emergent discipline devoted to figuring out why certain animals, plants, and microbes survive or even flourish no matter how much we transform their habitats. Humans rarely give much thought to the creatures that flit or crawl or skitter about our apartment blocks and strip malls, in part because we tend to dismiss them as either ordinary or less than fully wild. But we should instead marvel at how these organisms have managed to keep pace with our relentless drive to build and cluster in cities. Rather than wilt away as *Homo sapiens* have spread forth bearing concrete, bitumen, and steel, a select number of species have developed elegant adaptations to cope with the peculiarities of urban life: more rigid cellular membranes that may ward off heat, digestive systems that can absorb sugary garbage, altered limbs and torsos that enhance agility atop asphalt or in runoff-fattened streams.

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Whitehead and his colleagues, many of whom are at the dawn of their careers, are now beginning to pinpoint the subtle genetic changes that underlie these novel traits. Their sleuthing promises to solve a conundrum that has vexed biologists for 160 years, and in the process reveal how we might be able to manipulate evolution to make the world's cities—projected to be home to two-thirds of humanity by 2050—resilient enough to endure the catastrophes that are coming their way.

Weary as we are of despairing over the mass extinctions being caused by hyperdevelopment, it's tempting to take comfort in the ability of some animals to shrug off our brutalization of the planet. But the story that the pioneers of urban evolution are piecing together is tinged with darkness.

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For the first chunk of his career in evolutionary biology, Jason Munshi-South harbored all the standard romantic notions about which projects he should pursue. He studied the mating habits of tree shrews in Borneo and the demographics of elephants in Gabon, while earning his PhD from the University of Maryland and doing a postdoc at the Smithsonian. But in 2007, Munshi-South became an assistant professor at Baruch College in New York City, shortly after which his first child was born—two events that curtailed his globe-trotting. Restless, he looked for ways to scratch his fieldwork itch within range of the subway. His search for convenient subjects led him to study the white-footed mice that have colonized New York's parks.

Munshi-South and his assistants trapped scores of live mice and clipped off bits of their tails to get genetic material. Financial constraints and the state of technology at the time meant Munshi-South couldn't sequence the animals' entire genomes. Instead he used a shortcut called transcriptome analysis, which centers on the messenger RNA molecules that carry DNA's instructions for protein synthesis into cells. Since only the crucial bits of an organism's DNA get written into messenger RNA, researchers can work backward to infer, with impressive precision, the composition of the genes where it originated.

Munshi-South found there was scant gene flow between New York's various white-footed mouse populations—mice from the Bronx showed no signs of having recently mated with mice from Manhattan. Of greater note, however, were the sharp genetic differences between city mice and their country relatives: The city mice had conspicuous alterations in genes linked to metabolism, immune response, and detoxification. ("Linked," of course, is a word that oversimplifies the relationship: Traits are usually the product of a complex stew of interactions among genes and with the environment.)

As he sorted through the possible reasons for these changes, which included the need to tolerate a certain type of poisonous fungus, Munshi-South came to realize that his side project was destined to become his life's work. He was now enamored with the idea that urban cauldrons of noise, heat, and filth are not only as authentically "natural" as any other habitat but also the perfect venues in which to observe evolution at its fastest and most inventive. A bearded and slightly cherubic man, Munshi-South speaks engagingly about his epiphany despite the notable softness of his voice. "For most organisms, cities are incredibly stressful," he says. "So you'd expect that the evolutionary responses would have to be pretty strong for them to exist in that environment."

Munshi-South next turned his attention to *Rattus norvegicus*, the brown rat, an especially reviled New York City inhabitant. Though the rodents have been darting around America since colonial times, Munshi-South was stunned by how little was known about the genetic reasons for their success. "There was a golden age of rat research in Baltimore in the '40s and '50s, out of Johns Hopkins, which was mostly done in the interest of public health," he says. "They did

things we wouldn't be allowed to do, like they'd go catch 50 rats from one place and dump them in another place and see what happened. And that would basically cause a rat war." But no one in recent years had spent much time pondering whether rats might be evolving in sync with the cities where they abound.

Not long after moving to Fordham University in the Bronx in 2013, Munshi-South started setting traps in New York's dingiest nooks: subway platforms, storm drains, and the grease-slicked pavement outside pizza joints. (Unlike white-footed mice, brown rats tend to be too vicious to be collected alive.) In just a few years, the genetic tools at his disposal had become exponentially more advanced. It was now possible to sequence the whole genomes of individual rats for a reasonable price, and he could compare his results to a *Rattus norvegicus* reference genome that had been compiled as part of a federally funded project. Munshi-South and his collaborators found evidence that the genes controlling the olfactory sensors of New York's rats have been dramatically transformed by natural selection. The researchers believe the alterations in the genes' DNA sequences are linked to the rats' ability to navigate New York's subterranean passages, which are bathed in an ever-shifting barrage of smells.

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So when Munshi-South coauthored a 2017 *Science* review paper entitled "Evolution of Life in Urban Environments," he was able to list more than 100 recent and ongoing projects involving a range of city-dwelling organisms: moths that shed their species' fatal attraction to artificial lights, finches able to communicate above the din of traffic, swans that possess a genetic variant that makes them less nervous around humans.

When I asked Munshi-South why urban evolution is suddenly hot, I expected him to cite the proliferation of accessible DNA-sequencing technologies—an obvious boon to smaller, more unconventional labs like his that struggle for funding. But his primary explanation was more of a downer: He sees a kind of resignation to a dark environmental future, especially among younger biologists who have no memory of more idealistic days and who see little point in examining any instances of evolution that aren't driven primarily by human activity. "I don't want to call it capitulation," he says, "but it's kind of reconciling with our changed world."

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As a PhD student at the University of Massachusetts Boston, Winchell chose to focus on *Anolis cristatellus*, a lizard species native to Puerto Rico. She collected lizards in both unspoiled forests and from the densely populated neighborhoods of San Juan, Arecibo, and Mayagüez. She quickly noticed that every city lizard had significantly longer limbs and larger toe pads than their forest-dwelling counterparts—morphological differences that, unlike the majority of urban adaptations, can be seen with the naked eye.

To test how these differences affect locomotion, Winchell built a series of straight, 1.5-meter racetracks. The tracks were made from common Puerto Rican building materials such as painted concrete and aluminum sheeting. She then unleashed the lizards on these surfaces, and the city natives beat the country bumpkins without fail. The morphological changes had clearly made the city lizards consistently faster sprinters—a crucial fitness edge in urban environments, where the reptiles are vulnerable to feral cats and heat while skittering across wide-open expanses.

The lizard races may have been clever, but they didn't prove that the city lizards had actually evolved. Before even running the races, Winchell developed a way to show that the changes had a genetic component and were therefore heritable. Adaptations can often be the result of plasticity—the capacity of individual animals to change in response to stimuli during their lifetimes, yet remain unaltered at the genetic level. (Think of bodybuilders who manage to develop improbable physiques by subjecting their muscles to stress; their offspring do not inherit that appearance.)

Some urban evolution researchers fear that, in their rush to trumpet exciting results, fellow scientists aren't differentiating between plasticity and natural selection. "To only look at traits but not do it experimentally doesn't give you the opportunity to understand whether that trait is genetically based," says Max Lambert, a postdoc jointly at the University of Washington and UC Berkeley, who is studying how red-legged frogs are adapting to life in polluted stormwater ponds. "And overselling the field as being all urban evolution does a disservice to getting the public to understand what evolution is."

Mindful of the distinction between evolution and plasticity, Winchell conducted what is known as a common garden experiment. She collected adult lizards from Puerto Rico, bred them in her Boston lab, and then took eggs from both city and county lizards and hatched them in an incubator. Once the babies hatched, she distributed them to isolated cages in which the conditions were identical: Each contained a single turtle vine and a wooden rod measuring three-quarters of an inch in diameter, for example, and each was bathed in 12 hours of UV light per day. After a year of raising the lizards on live crickets dusted with vitamins, Winchell examined their legs and toes. Her measurements and observations, which she published in a 2016 paper in the journal *Evolution*, confirmed that the urban lizards were true products of rapid evolution.

Winchell, who intends to investigate the evolution of squirrels and raccoons in St. Louis, Boston, and New York, understands that her work might provide a rare source of hope for those anguished by depressing environmental news. "People didn't think animals could adapt on human time scales," she says. "So people are excited that some animals are dealing with what we're doing to them." Those survivors, though relatively few in number, possess genes that have much to tell us about how to prepare for our hostile future.

As the severity of the climate crisis becomes more apparent with each record-breaking heat wave or melting slab of Arctic ice, humankind is coming to terms with the fact that much of the damage we've wrought is irreversible. That means making peace with the permanent disappearance of a fair portion of the animal kingdom: According to a May report from the United Nations, at least 1 million species are in imminent danger of extinction, including 40 percent of amphibians and a third of marine mammals. Even if all nations were to magically cooperate and take unprecedented steps to protect biodiversity, it would be too late for thousands of species.

Like so many of their scientific peers, urban evolution researchers are grappling with the question of how their work can help us make this new environmental reality a bit less grim. On the surface, at least, their inquiries can seem largely aimed at addressing theoretical matters—notably the issue of whether the evolution of complex organisms is a replicable phenomenon, like any ordinary chemical reaction. Cities provide an accidental global network of ad hoc laboratories to test this question: Office towers the world over are fabricated from the same glass panels and steel beams, night skies are illuminated by the same artificial lights, auditory landscapes thrum with the noise of the same cars, food waste comes from the same KFCs and Subways.

This urban sameness is allowing researchers to determine whether isolated populations of the same species develop similar adaptations when placed in parallel environments. “What cities offer us is this amazingly large-scale, worldwide experiment in evolution, where you've got thousands of life-forms that are experiencing the same factors,” says Marc Johnson, who heads an evolutionary ecology lab at the University of Toronto Mississauga.

Laypeople can be forgiven for not instinctively sharing that enthusiasm, however: At first glance, settling the decades-long debate over evolution's replicability doesn't appear likely to make our post-climate-change lives any less hellish.

But in the quest to satisfy their intellectual curiosity, urban evolution researchers are also revealing the fundamental genetic attributes that make some species adept at adjusting to urban life—intelligence that could give us the power to forecast evolution's winners and losers in a world that's increasingly hot and crammed with people. When he concluded that killifish in four US cities had developed the same form of toxin resistance, for example, Andrew Whitehead ascribed the species' evolutionary success to its high degree of genetic diversity—that is, the killifish genome naturally contains an abundance of genetic information that isn't usually expressed. So the key to desensitizing the aryl hydrocarbon receptor was probably already present inside killifish DNA, and natural selection simply brought it to the fore.

“When the environment changes very rapidly, and changes in a way that poses fitness challenges, then species that are going to be able to adaptively respond to that are ones that already have the necessary genetic diversity in hand,” Whitehead says. “The environment is changing right now. You can't wait for migrants. You can't wait for new mutations.”

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Perhaps the greatest asset any creature can have hidden in its genome, of course, is the capacity to withstand heat. With global temperatures set to rise by as much as 9 degrees Fahrenheit by the turn of the century, the species likeliest to survive will be those that develop traits to guard against the broil. Today's cities, which are typically 2 to 5 degrees warmer than their surroundings, offer a sneak preview of how evolution will reshape wildlife on a sweltering planet.

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Certain urban design choices can help us nudge evolution in whatever directions we choose. It is in our best interest, for example, to encourage the proliferation of the frogs that have adapted to living in man-made ponds where both storm runoff and toxic chemicals collect. These amphibians prey on mosquitoes and other insects that can carry disease, a threat likely to increase as the world heats up. So it would be smart to establish connections between ponds where the pollution-resistant frogs are abundant and those they've yet to colonize—say, by digging narrow tunnels beneath roadways. Bats are also desirable in cities for their pest-control talents; can we encourage them to adapt to urban areas by favoring particular types of artificial light, or by making sure the sonic environment won't interfere with the way they hunt?

Granted, a certain amount of hubris is required to believe we'll soon master the wondrous mechanism that turned lone cells into whales and giraffes in a mere few billion years. But as evidenced by the terrible environmental bind we've gotten ourselves into, hubris is what *Homo sapiens* do best.

Questionário:

1) 1) Como a população de killfishes da baía de Newark sobrevive com a presença de dioxina?
2) Por que os killfishes que vivem em habitats com alta poluição química são uma evidência que a evolução pode ser previsível?
3) Por que ambientes urbanos são particularmente adequados para estudos de biologia evolutiva?
4) Como a perspectiva do futuro pode ter influenciado as pesquisadoras que escolheram estudar a biologia evolutiva em ambientes urbanos?
5) Como foi possível determinar que as diferenças morfológicas entre os exemplares urbanos e florestais de *Anolis cristatellus* tem um forte componente genotípico?
6) Que propostas o autor sugere para melhorar a qualidade de vida das cidades aproveitando a fauna urbana?